REMARKS

Claims 1 through 31 of the substitute specification have been canceled without prejudice. New Claims 32 through 61 are added. Thus, by this preliminary amendment, Claims 32 through 61 are presented for initial examination in the U.S. national phase of PCT/EP2004/004845.

The amendments to the claims are made to conform the application to German patent application 103 20 674.4, from which Convention priority is claimed, as amended by the response filed July 13, 2004. Such response was filed to address the office action of March 2, 2004 of the German Patent Office.

No new matter is added by the changes made herein.

Respectfully submitted,

Elliott N. Kramsky
Registration 27,812
Attorney for Applicant

Title: PULSE MODULATOR AND METHOD FOR PULSE MODULATION

Inventor: Guenter Spahlinger

BACKGROUND

Field of the Invention

The present invention relates to pulse modulators. More specifically, the invention pertains to a pulse modulator for conversion of a complex input signal to a pulsed signal, and to a method for pulse modulation of a complex input signal.

Description of the Prior Art

Digital/analog converters may be employed ~~used~~ to convert ~~a~~ digital input signals ~~signal~~ to ~~an~~ analog signals ~~signal~~. They are, however, ~~these modules are~~ expensive and require a relatively large amount of electrical power as well as a number of supply voltages ~~are~~ (frequently). ~~required. A further disadvantage is that digital/analog converters~~ They are also difficult to integrate with ~~the~~ digital electronics and, thus, limit ~~restrict~~ miniaturization.

As a result, digital/analog converters are ~~thus~~ being replaced by digital pulse modulators (e.g. ~~such as~~ sigma-delta converters) in many applications. A

conventional sigma-delta modulator includes ~~has~~ an integrator that ~~which~~ integrates the difference signal between an ~~the~~ input signal and a fed-back quantized signal, as well as a quantizer that ~~which~~ quantizes the integrated signal. A quantized pulsed signal can then be tapped off at the output of the quantizer. It ~~and~~ is fed back as a feedback signal to the input of the sigma-delta converter. Sigma-delta modulators are distinguished by a ~~typical~~ noise characteristic in which ~~with~~ the quantization noise is ~~being~~ shifted from the low-frequency range in the vicinity of ω=0 towards higher frequencies. The noise that ~~which~~ occurs at ~~in the region of~~ higher frequencies can then be suppressed with the aid of a downstream low-pass filter. Sigma-delta converters can be implemented with ~~at~~ low cost and ~~can be~~ integrated with ~~the~~ digital electronics. However, for some applications, it would be advantageous to be able to keep the quantization noise low at ~~in~~ higher frequencies. ~~low.~~

SUMMARY AND OBJECTS OF THE INVENTION

It is therefore an ~~One~~ object of the invention ~~is thus~~ to provide a pulse modulator and ~~as well as~~ a method for pulse modulation, in which the spectral distribution of ~~the~~ quantization noise can be flexibly adapted.

~~This object of the invention is achieved by a pulse modulator for conversion of a complex input signal to a pulsed signal as claimed in claim 1, by a drive circuit as claimed in claim 16, by a frequency generator as claimed in claim 19, and by a method for pulse modulation of a complex input signal as claimed in claim 21. Claim 31 relates to a computer program product for carrying out the method according to the invention.~~

The <u>present addresses the preceding object by providing, in a first aspect, a</u> pulse modulator ~~according to the invention~~ for conversion of a complex input signal to a pulsed signal. <u>Such modulator includes</u> ~~has~~ a subtraction stage <u>that</u> ~~which~~ produces a control error signal from the difference between the complex input signal and a feedback signal. ~~The pulse modulator furthermore has~~ A signal conversion stage <u>is provided that</u> ~~which~~ converts the control error signal to a control signal. <u>A first multiplication stage multiplies</u> the control signal ~~is multiplied~~ by a complex mixing signal oscillating at the frequency ω_0 ~~in a first multiplication stage, thus producing~~ <u>to produce</u> at least one of a real part and <u>an</u> imaginary part of a control signal <u>that</u> ~~which~~ has been up-mixed by ω_0. ~~The pulse modulator furthermore has~~ A quantization stage ~~which~~ quantizes at least one of the real part and imaginary part of the control signal

that ~~which~~ has been up-mixed by ω_0 and thus produces the pulsed signal. ~~as well as~~ A feedback unit ~~which~~ uses the pulsed signal to produce the feedback signal for the subtraction stage.

These features and description is accompanied by a set of drawing figures. Numerals of the drawing figures, corresponding to those of the written description, point to the features of the invention. Like numerals refer to like features throughout both the written text and the drawing figures.

In a second aspect the invention provides a method for pulse modulation of a complex input signal. Such method includes the production of a control error signal from the differences between the complex input signal and a feedback signal. The control error signal is then converted to a control signal.

The control signal is multiplied by a complex mixing signal that oscillates at the frequency ω_0. At least one of the real and imaginary parts of a control signal, up-mixed by ω_0, is produced. At least one of the real and imaginary parts of the control signal, up-mixed by ω_0, is quantized to produce a pulsed signal. The feedback signal is then produced from the pulsed signal.

The preceding and other features of the invention will become further apparent from the detailed description that follows. Such description is accompanied by a set of drawing figures. Numerals of the drawing figures, corresponding to those of the written description, point to the features of the invention. Like numerals refer to like features throughout both the written text and the drawing figures.

BRIEF DESCRIPTION OF THE DRAWINGS

~~The invention and further advantageous details will be explained in more detail in the following text with reference to the drawings, which are in the form of exemplary embodiments and in which:~~

Figure 1 is ~~shows~~ a ~~complex~~ block diagram of a ~~the~~ pulse modulator in accordance with ~~according to~~ the invention;

Figure 2 is ~~shows~~ a block diagram of a ~~the~~ pulse modulator, with ~~showing~~ the in-phase path and the quadrature path shown separately;

Figure 3 illustrates ~~shows~~ a ternary-quantized pulsed signal y(t);

Figure 4 is a graph of the ~~shows a~~ frequency spectrum of the pulsed signal y(t) produced at the output of the quantizer;

Figure 5 is a graph of ~~shows~~ the frequency spectrum of the preceding figure ~~from Figure 4~~ after filtering by a micromechanical oscillator;

Figure 6 is a graph of the ~~shows a~~ frequency spectrum of a pulsed signal y(t) ~~which has been~~ plotted for a ratio of the mixing frequency to the sampling frequency of $\omega_0/\omega_A = 0.25$;

Figure 7 is a block diagram of ~~shows~~ a pulse modulator with statistical rounding;

Figure 8 is a graph of ~~shows~~ the frequency spectrum of ~~from~~ Figure 6 with statistical rounding; ~~being carried out~~ and

Figure 9 is ~~shows~~ a block diagram of a two-dimensional pulse modulator.

BRIEF DESCRIPTION OF THE PREFERRED EMBODIMENT

Figure 1 is ~~shows~~ a block diagram of a ~~the~~ pulse modulator in accordance with ~~according to~~ the invention in

complex form. A ~~The~~ complex input signal x(t) includes ~~has a~~ real ~~part~~ and ~~an~~ imaginary parts, ~~part which are both~~ each represented as digital values. A ~~The~~ complex feedback signal 2 is subtracted from the complex input signal x(t) in the addition node 1, with their ~~the~~ difference ~~between these two complex signals~~ representing the control error. ~~Furthermore,~~ The (likewise complex) content of a ~~the~~ delay element 3 is added to such ~~this~~ difference at ~~in~~ the addition node 1. (The content of the delay element 3 is passed via a ~~the~~ signal line 4 to the addition node 1.) The delay element 3, combined ~~together~~ with the signal line 4, forms a complex integrator stage that ~~which~~ integrates the complex control error (i.e. ~~that is to say~~ the difference between the input signal and the feedback signal). The integrated signal 5 is amplified by a ~~the~~ factor "a" in an ~~the~~ amplifier stage 6. An ~~and the~~ amplified signal 7 is passed to a ~~the~~ first multiplication stage 8 where it ~~the amplified signal 7~~ is multiplied by the complex mixing signal $e^{j \cdot \omega_0 t}$ ~~in order in this way~~ to obtain a ~~the~~ signal 9 up-mixed to ~~the~~ frequency ω_0. A ~~The~~ block 10 determines the real part 11 of the complex up-mixed signal 9 and this is applied ~~and the real part 11, obtained in this way, of the up-mixed signal is made available~~ to a ~~the~~ quantizer 12.

The quantizer 12 of ~~In~~ the embodiment of ~~shown in~~ Figure 1 is in the form of a ternary quantizer that ~~which~~ converts the ~~respective~~ input signal to the three possible values -1, 0, +1 of a pulsed signal with the aid of comparators. The quantized pulsed signal y(t) thus produced ~~in this way~~ can be tapped off at the output of the quantizer 12. The real pulsed signal y(t) is multiplied in a ~~the~~ second multiplication stage 13 by the complex-conjugate mixing signal $e^{-j\omega_0 t}$ ~~in order~~ to produce the complex feedback signal 2. The complex feedback signal 2, ~~which is~~ obtained ~~in this way~~ by multiplication of a real ~~number~~ and a complex number, is passed to the addition node 1 at the input to the circuit.

The sequence of functional units illustrated in Figure 1 can be implemented by means of a digital signal processor (DSP) or ~~else~~ by ~~means of~~ dedicated hardware. ~~that is specifically provided for this purpose.~~ The digital signal processing must ~~in this case~~ be carried out at a sampling frequency ω_A that ~~which~~ is considerably higher than the frequency ω_0 of the complex mixing signal ~~For example~~ (e.g. 2 to 1000 times the mixing frequency ω_0 may be used as the sampling rate ω_A).

Figure 2 is a block diagram of ~~once again shows~~

the pulse modulator of ~~illustrated in~~ Figure 1, with the in-phase signal path and the quadrature signal path ~~in this case being~~ shown separately. The upper half of Figure 2 shows the in-phase signal path 14, which processes the real part R of the input signal x(t). The lower half of Figure 2 shows the quadrature signal path 15 for processing ~~of~~ the imaginary part I of the input signal. The real part of the control error is determined at ~~in~~ the addition node 16 of ~~in~~ the in-phase path as the difference between the real part R of the input signal and the real part 17 of the feedback signal. The integrator value, ~~which has been~~ stored ~~until then~~ in a ~~the~~ delay element 18, is added to this control error and ~~is~~ passed via a ~~the~~ signal line 19 to the addition node 16. ~~Together with~~ The signal line 19, combined with the delay element 18, form ~~forms~~ an integrator with the transfer function

$$H(z) = \frac{1}{z-1}.$$

The addition of the real part of the control error to the previous integrator value produces ~~results in~~ a new integrator value that ~~which~~ is once again stored in the delay element 18. The integrated signal 20 in the in-phase signal path is scaled by the factor "a" of an ~~by the~~ amplifier 21, and is then passed as an ~~the~~ amplified

signal 22 to <u>a</u> ~~the~~ first multiplier 23. The first multiplier 23 multiplies the real, amplified signal 22 by the real signal $\cos(\omega_0 t)$, <u>(i.e.</u> ~~that is to say~~ by the real part of $e^{-j\omega_0 t}$ <u>)</u>. The first multiplier 23 determines the product $R \bullet \cos(\omega_0 t)$, which is supplied as <u>a</u> ~~the~~ signal 24 to <u>an</u> ~~the~~ adder 25.

The quadrature signal path 15 of the pulse modulator <u>includes</u> ~~has~~ an addition node 26 in which the difference between the imaginary part I of the input signal and <u>an</u> ~~the~~ imaginary part 27 of the feedback signal is calculated. This difference, which corresponds to the imaginary part of the control error, is added to the previous content of <u>a</u> ~~the~~ delay element 28 <u>that</u> ~~which~~ is passed to the addition node 26 via <u>a</u> ~~the~~ signal line 29. The new value, which is obtained as the sum of the previous value and ~~of~~ the imaginary part of the control error, is written to the delay element 28. Together with the signal line 29, the delay element 28 forms an integrator with the transfer function $H(z) = \frac{1}{1-z^{-1}}$. The integrated signal 30 from the quadrature signal path is produced at the output of <u>the</u> ~~this~~ integrator, and is scaled by the factor "a" <u>of an</u> ~~by the~~ amplifier 31. <u>An</u> ~~The~~ amplified signal 32 obtained ~~in this way in the quadrature~~

~~signal path~~ is then multiplied by the signal $\sin(\omega_0 t)$ in a ~~the~~ second multiplier 33. The product $I \bullet \sin(\omega_0 t)$ obtained in this way is supplied as a ~~the~~ signal 34 to the adder 25. The adder 25 adds the signals $R \bullet \cos(\omega_0 t)$ and $I \bullet \sin(\omega_0 t)$ and produces the signal $R \bullet \cos(\omega_0 t) + I \bullet \sin(\omega_0 t)$ as a ~~the~~ signal 35. ~~at its output. However, this~~ The signal 35 corresponds precisely to the real part of the up-mixed signal as ~~because~~ the complex multiplication of x(t) and $e^{-j\omega_0 t}$ shows: ~~gives:~~

$$x(t) \bullet e^{-j\omega_0 t} =$$

$$= (R + j \bullet I) \bullet (\cos(\omega_0 t) - j \bullet \sin(\omega_0 t)) =$$

$$= [R \bullet \cos(\omega_0 t) + I \bullet \sin(\omega_0 t)] + j \bullet [I \bullet \cos(\omega_0 t) - R \bullet \sin(\omega_0 t)]$$

~~and~~ The real part of this signal is $R \bullet \cos(\omega_0 t) + I \bullet \sin(\omega_0 t)$. The signal 35 thus represents the real part of the complex up-mixed signal, and, to such ~~this~~ extent, corresponds to the signal 11 illustrated in Figure 1.

The digital real signal 35 is applied ~~passed~~ to a ~~the~~ quantizer 36 that ~~which~~ converts it ~~this input signal~~ to the quantized pulsed signal y(t). The three-stage (ternary) quantizer of ~~shown in the example in Figure~~ Figures 1 and ~~Figure~~ 2 quantizes the input signal on the basis $y(t) \in \{-1; 0; +1\}$. For this, ~~purpose~~ the

quantizer 36 includes ~~has~~ comparators that ~~which~~ continuously compare the ~~signal~~ level of the signal 35 with predetermined threshold values. Depending on the result of such ~~these~~ comparisons, the output signal y(t) is assigned one of the values -1; 0; +1 in each case as the current signal value. Instead of ~~the~~ three-stage (ternary) quantization, ~~any~~ other desired quantizations may be employed ~~used~~ depending on the purpose ~~for example~~ (e.g. two-stage (binary) or multiple-stage quantizations).

The real part 17 and the imaginary part 27 of the complex feedback signal are derived from the quantized pulsed signal y(t). For this, ~~purpose~~ the pulsed signal y(t) is multiplied by the complex-conjugate mixing signal $e^{j\omega_0 t}$:

$$y(t) \bullet e^{j\omega_0 t} = y(t) \bullet \cos(\omega_0 t) + j \bullet y(t) \bullet \sin(\omega_0 t)$$

The real part $y(t) \bullet \cos(\omega_0 t)$ of the complex feedback signal is produced by the third multiplier 37, that ~~which~~ multiplies the pulsed signal y(t) by $\cos(\omega_0 t)$. The real part 17 of the feedback signal is thus produced at the output of the third multiplier 37 and ~~is~~ fed back to the addition node 16. In order to produce the imaginary part $y(t) \bullet \sin(\omega_0 t)$ of the complex feedback signal, the

pulsed signal y(t) is multiplied by $\sin(\omega_0 t)$ at ~~in~~ the fourth multiplier 38. The imaginary part 27 of the feedback signal is produced at the output of the fourth multiplier 38 and ~~is~~ fed back to the addition node 26.

Integrators are provided on the input side in the exemplary embodiments of ~~shown in~~ Figures 1 and 2 that ~~which~~ integrate the control error existing between the input signal and the feedback signal to ~~and thus~~ produce an integrated signal. The transfer function H(z) of an integrator can be represented ~~written as~~ $H(z) = \frac{1}{z-1}$.

Other signal conversion stages (with other transfer functions H(z)) may ~~also~~ be employed ~~used~~ on the input side rather than ~~instead of~~ the integrators. For example, higher-order transfer functions H(z) may ~~could~~ be used in which case, however:

$$\lim_{z \to 1} H(z) = \infty$$

The transfer function H(z) should thus tend to infinity as ~~for the situation in which~~ the frequency ω tends to ~~the value~~ zero (z→1). The additional free parameters of H(z) may be employed ~~used~~ to optimize

specific characteristics of the modulator (e.g. ~~for example the~~ signal-to-noise ratio) or of the overall system.

Figure 3 illustrates ~~shows~~ the waveform of the pulsed signal $y(t)$ that ~~which~~ can be tapped off at the output of the quantizer for ~~the situation of~~ ternary quantization with $y(t) \in \{-1; 0; +1\}$ ~~which was~~ determined by ~~with the aid of a~~ computer simulation. ~~In this case,~~ The real part R of the complex input signal was set to 0.3, while the imaginary part I of the input signal was set to ~~be equal to~~ zero. The input signal $x(t)$ is thus constant and does not vary with ~~as a function of~~ time. The sampling frequency ω_A was set ~~is~~ five times ~~as great as~~ the mixing frequency $\omega_0/\omega_A = 0.2$. ~~The~~ Clock pulses at the sampling frequency ω_A are shown on the abscissa, ~~and are~~ numbered successively from 5000 to 5100. During each clock cycle, the pulsed signal $y(t)$ assumes one of the three possible values -1; 0; +1. The ~~respective~~ value of $y(t)$ during one specific clock cycle at the sampling frequency is plotted on ~~in~~ the ~~direction of the~~ ordinate.

Figure 4 is a graph of the spectrum of the pulsed signal of Figure 3 from ~~If~~ a spectral analysis (FFT). ~~is carried out on the pulsed signal illustrated in Figure 3, this results in the spectrum shown in Figure 4.~~

The frequencies ~~frequency~~ of the ~~respective~~ spectral components are ~~is~~ shown in arbitrary FFT units on the abscissa while ~~the~~ signal intensity is plotted in dB on ~~in the direction of~~ the ordinate. A peak can be seen in the spectral distribution at ~~the~~ frequency ω_0. It can also be seen that the noise level in the vicinity of ~~the frequency~~ ω_0 is considerably less than in the remaining part of the spectrum. In a conventional sigma-delta modulator, the noise level would, in contrast, be considerably reduced at low frequencies ~~that is to say~~ (i.e. in the vicinity of ~~the frequency~~ ω_0). In a ~~the case of the~~ pulse modulator in accordance with ~~according to~~ the invention, the integrated and amplified signal is up-mixed to the mixing frequency ω_0 by ~~means of~~ a complex multiplication. ~~In consequence,~~ As a result, the spectral range over ~~in~~ which the noise is reduced is also shifted toward the mixing frequency ω_0, ~~thus~~ resulting in the noise characteristic of the graph of ~~illustrated in~~ Figure 4.

The pulse modulator of ~~according to~~ the invention may ~~can~~ be used for digital synthesis of a pulsed signal. In this ~~which~~ case, the main spectral component of the pulsed signal can be predetermined by the mixing frequency ω_0. The phase angle of the pulsed signal ~~that is~~ produced can be set exactly by the ratio of the real ~~part~~ to the imaginary part of the input signal. ~~and~~

This results in a pulsed signal whose phase is stable.

When using a ~~the~~ pulse modulator in accordance with ~~according to~~ the invention for frequency synthesis, the pulsed signal y(t) should be filtered by means of an electrical bandpass filter, whose passband is centered around the frequency ω_0. Such a ~~This bandpass~~ filter which may, for example, be in the form of a crystal or ceramic filter, makes it possible to suppress spectral ranges further removed ~~away~~ from ω_0 ~~in which~~ where the noise level is undesirably high. A bandpass filter such as this makes it possible to significantly improve the signal-to-noise ratio.

The pulse modulator of ~~according to~~ the invention is suitable, inter alia, for stimulation of electromechanical oscillators to carry out harmonic oscillations. In particular, the electrostatic forces ~~which are~~ required for oscillation stimulation can be produced by ~~means of~~ a ternary-quantized pulsed signal ~~which is~~ applied to the stimulation electrodes of a micromechanical resonator. The frequency ω_0 of the pulsed signal y(t) is preferably chosen to be equal to the resonant frequency of the micromechanical oscillator in this case. If the pulsed signal, as illustrated in Figures ~~Figure~~ 3 and ~~Figure~~ 4, is used for harmonic stimulation of

a high Q-factor oscillator (e.g. ~~for example~~ with a Q-factor of 10^4), whose resonant frequency corresponds to the stimulation frequency ω_0, ~~then~~ the majority of the quantization noise is filtered out by the oscillator. ~~itself~~ ~~In particular~~ That is, the quantization noise in spectral ranges further removed ~~away~~ from the resonant frequency ω_0 is suppressed by the oscillator itself. The filtered spectrum obtained in this way is illustrated by the graph of ~~shown in~~ Figure 5.

Specific ratios of the frequencies ω_0/ω_A exist that result in conversion of ~~for which~~ the noise-like quantization product in y(t) ~~is converted~~ to a series of more or less periodic functions. An ~~As one~~ example is, illustrated in ~~of this,~~ Figure 6, ~~shows~~ a graph of the frequency spectrum ~~which was~~ obtained for the ratio $\omega_0/\omega_A = 0.25$. A range of spectral lines 39, 40, 41, etc. can be seen in addition to the peak at ~~the frequency~~ ω_0. ~~The reason for the creation of these~~ Such spectral lines result from the fact ~~is~~ that the quantizer is a highly non-linear element in the control loop. ~~because~~ This stimulates relaxation oscillations in the control loop with certain frequency ratios. Such ~~This~~ control loop response is recognized to exist in ~~known from~~ conventional delta-sigma converters.

~~In order~~ The central linearity of the quantizer can be improved by adding a noise signal to the input signal to prevent the creation of relaxation oscillations. ~~to the quantizer~~ A spectrally uniformly distributed noise signal is preferably employed ~~used~~ for this purpose. Figure 7 is a ~~shows the~~ block diagram of a correspondingly modified pulse modulator. In comparison to the block diagram of ~~shown in~~ Figure 2, the pulse modulator of ~~shown in~~ Figure 7 additionally comprises ~~has~~ a noise generator 42 that ~~which~~ produces a noise signal 43. Also, ~~In addition,~~ the integrators ~~which are~~ shown in Figure 2 are illustrated in a generalized form as signal conversion stages 44, 45 with ~~the~~ transfer function H(z). Otherwise, the assemblies of ~~shown in~~ Figure 7 correspond to the elements of the block diagram of ~~in~~ Figure 2. The noise signal 43 is supplied to the adder 25, where it is added to the signals 24 and 34. The signal 35 at the input of the quantizer 36 thus ~~therefore~~ has a noise signal superimposed on it. ~~and, in the end,~~ This eventually leads to statistical rounding in the quantization process. The graph of Figure 8 illustrates ~~shows~~ the frequency spectrum of a pulsed signal y(t) ~~which was~~ produced with the aid of a pulse modulator modified as shown in Figure 7. Although the frequency ratio ω_0/ω_A is once again equal to 0.25, no relaxation oscillations are formed.

The pulse modulator of ~~according to~~ the invention can be used, in particular, for electrostatic stimulation of micromechanical oscillators. For such ~~this~~ purpose, by way of example, a ternary-quantized pulsed signal of the type shown in Figure 3 can be connected to the stimulation electrodes of a micromechanical resonator. The pulsed signal of ~~shown in~~ Figure 3 represents a sinusoidal signal of ~~at the~~ frequency ω_0. Such a pulsed signal ~~such as this~~ can ~~thus~~ be used to stimulate a micromechanical resonator to carry out harmonic oscillations at the frequency ω_0. This is particularly true ~~to be precise in particular~~ when the frequency ω_0 of the pulsed signal corresponds (at least approximately) to the resonant frequency of the oscillator.

Resonators that ~~which~~ can oscillate in two mutually perpendicular directions y_1 and y_2 are employed ~~used~~ in rotation rate sensors and Coriolis gyros. The two-dimensional pulse modulator illustrated ~~shown~~ in Figure 9 may be employed ~~used~~ for electrostatic stimulation of a two degree of freedom resonator ~~with~~. The two-dimensional pulse modulator has a first pulse modulator 46 that ~~which~~ produces the pulsed signal $y_1(t)$ from the complex input signal R_1, I_1. ~~and this~~ The pulsed signal is used to stimulate the resonator in the y_1 direction. The pulsed signal $y_2(t)$ is produced from the complex input signal R_2,

I_2 by a ~~the~~ second pulse modulator 47. ~~and~~ This pulsed signal is employed ~~used~~ to stimulate the oscillator to oscillate in the y_2 direction. Both the first pulse modulator 46 and the second pulse modulator 47 are of ~~in~~ the type ~~form~~ of a pulse modulator with statistical rounding as shown in Figure 7. A description of the design and method of operation of the first and ~~of the~~ second pulse modulators ~~modulator~~ 46, 47 can thus ~~therefore~~ be found in the portion of the description ~~of the figures~~ relating to Figures 2 and 7. However, the two-dimensional pulse modulator of ~~shown in~~ Figure 9 includes a ~~has one~~ 2D quantizer 48 ~~which is~~ shared by the two channels. ~~and~~ It converts the signal 49 of the first pulse modulator 46 to the quantized pulsed signal $y_1(t)$ and transforms the signal 50 of the second pulse modulator 47 to the quantized pulsed signal $y_2(t)$.

The use of a 2D quantizer 48 ~~which is~~ shared by the two channels makes it possible to take into account additional conditions ~~which are~~ advantageous for operation of the micromechanical sensor during ~~the~~ quantization of the signals 49, 50. One such additional condition for ~~by way of~~ example, is that in each case only one of the channels may produce pulses other than zero. Another feasible additional condition is that only one of the output signals $y_1(t)$, $y_2(t)$ may change in each case at any

given time. Additional conditions ~~such as these~~ may be worthwhile when the displacement currents ~~which are~~ applied to the electrodes of a double resonator are measured in sum form, making ~~in order to make~~ it possible to deduce the deflection of the oscillator. The additional conditions make it possible to associate a displacement current unambiguously with one specific electrode. This makes it possible to carry out signal separation between the signals caused by the y_1 ~~deflection~~ and ~~the~~ y_2 deflections ~~deflection~~ of the oscillator.

In summary, the ~~method of~~ operation of a ~~the~~ pulse modulator in accordance with ~~according to~~ the invention ~~which~~ represents an advantageous modification of a conventional sigma-delta converter. It has been ~~will be~~ explained ~~in the following text~~ for the example of an input signal that is kept constant without any restriction to generality. The subtraction ~~stage~~ and ~~the~~ signal conversion stages ~~stage~~ convert the ~~this~~ input signal to a control signal that also ~~which likewise~~ varies only slightly in time. In contrast to conventional sigma-delta converters, the ~~this~~ control signal is, however, now multiplied by the first multiplication stage by a complex mixing signal at the frequency ω_0 ~~in order in this way~~ to produce a control signal up-mixed to the frequency ω_0. The real ~~part~~ or the imaginary part of the ~~this~~ control

signal, oscillating at the frequency ω_0, is then quantized by the quantization stage, ~~thus~~ resulting in a real pulsed signal with a dominant frequency component at the frequency ω_0 at the output of the quantization stage. The ~~This~~ real pulsed signal, together with the aid of positive or negative pulses, simulates a sinusoidal signal at the frequency ω_0. Such ~~This~~ pulsed signal represents the point of origin for the calculation of the feedback signal at the same time. ~~which~~ Such feedback signal is fed back to the subtraction stage where it is subtracted from the input signal ~~in order~~ to determine the control error.

~~In order~~ It is not absolutely essential to calculate both the real part and the imaginary part of the control signal up-mixed by ω_0 to produce the pulsed signal. If the intention is to derive the pulsed signal from the real part of the up-mixed control signal, ~~then~~ the imaginary part of the up-mixed control signal need not necessarily be produced.

The major advantage of the pulse modulator of ~~according to~~ the invention over conventional sigma-delta modulators is that the range of low quantization noise is shifted from ~~the low-frequency range in~~ the vicinity of $\omega=0$ toward the operating frequency ω_0. This is achieved by complex up-mixing of the control signal in the first

multiplication stage. ~~This~~ It results in a pulsed signal that ~~which actually~~ has a low noise level in the relevant spectral range around ω_0.

The starting point for understanding ~~of~~ the noise characteristic is that the signal conversion stage which may be formed, for example, by an integrator, has a low-pass characteristic. This means that relatively high-frequency components are partially suppressed by the signal conversion stage. In conventional sigma-delta converters, this suppression of the higher-frequency components in the control loop causes a rise in the quantization noise at ~~these~~ higher frequencies. In contrast, the quantization noise in the low-frequency range is low. In the case of the pulse modulator of ~~according to~~ the invention, the control signal, which can be tapped off at the output of the signal conversion stage, is up-mixed to the frequency ω_0 by multiplication by the complex mixing signal at the frequency ω_0. The range of low quantization noise is thus also shifted from the frequency $\omega=0$ toward the mixing frequency ω_0, even though the signal conversion stage on the input side is still processing a signal which has not been up-mixed. This results in a pulsed signal with a noise level which is low in the vicinity of ω_0.

The pulse modulator according to the invention can be implemented at low cost, requires relatively little electrical power, and can easily be integrated together with the digital electronics.

It is advantageous for the pulse modulator to have an in-phase signal path for processing of the real part of the input signal, as well as a quadrature signal path for processing of the imaginary part of the input signal. It is also advantageous for the control error signal, the control signal and the feedback signal ~~each~~ to be complex signals with ~~which~~ each having ~~have~~ a real signal component as well as an imaginary signal component. ~~In order~~ To insure ~~ensure~~ that the real pulsed signal reflects the real ~~part~~ or the imaginary part of the control signal up-mixed by ω_0 in the correct phase, the subtraction stage, the signal conversion stage, the first multiplication stage and the feedback unit are complex signal processing units which ~~each~~ have an in-phase signal path and a quadrature signal path. ~~However~~ Only the real part (or ~~else~~ the imaginary part) of the output signal from the first multiplication stage is required ~~in order~~ to derive the real pulsed signal from it with the aid of the quantization stage. The quantization stage may thus be a real processing stage. In fact, the real pulsed signal is then once again converted to a complex feedback signal

in the feedback unit. This design of the pulse modulator makes it possible to synthesize a real pulsed signal, which reproduces a harmonic oscillation at the frequency ω_0 with low phase and amplitude noise, with the correct phase.

According to one advantageous embodiment of the invention, the signal conversion stage has an integrator stage that ~~which~~ integrates the control error signal and produces an integrated signal as the control signal. Integration of the control error signal makes it possible to slave the (complex) integrated signal continuously to the complex input signal. Since an integrator stage has a low-pass filter characteristic, this results in a control signal at the output of the integrator stage with a reduced noise level in the region around ω_0. If this control signal is then up-mixed by the first multiplication stage, and ~~is~~ then quantized, ~~this results in~~ a pulsed signal with the desired noise characteristic results.

It is advantageous for the integrator stage to have a first integrator for the in-phase signal path and a second integrator for the quadrature signal path. ~~with~~ The first integrator integrates ~~integrating~~ the real part of the control error signal and ~~with~~ the second integrator

integrates ~~integrating~~ the imaginary part of the control error signal. A complex integrator stage for the complex control error signal can be produced with the aid of two separate integrators in this way.

It is advantageous for the signal conversion stage to have an amplifier stage. The gain factor is chosen such that the quantizer receives the correct input signal level in this case.

According to a further advantageous embodiment of the invention, the first multiplication stage has a first multiplier for the in-phase signal path and a second multiplier for the quadrature signal path. The first multiplier multiplies the real part of the control signal by the real part of the complex mixing signal oscillating at the frequency ω_0, and thus produces a first result signal. The second multiplier multiplies the imaginary part of the control signal by the imaginary part of the complex mixing signal oscillating at the frequency ω_0, and thus produces a second result signal. According to a further advantageous embodiment, the pulse modulator has an adder that ~~which~~ adds the first result signal from the first multiplier and the second result signal from the second multiplier to form a sum signal ~~in order~~ to determine the real part of the up-mixed control signal.

If it is assumed that the complex control signal is in the form R+j•I, and, by way of example, the complex mixing signal is represented in the form $e^{-j\cdot\omega_0 t}$, then the first result signal from the first multiplier becomes $R\bullet\cos(\omega_0 t)$. The second result signal from the second multiplier assumes the form $I\bullet\sin(\omega_0 t)$, and the adder produces the signal $R\bullet\cos(\omega_0 t)+I\bullet\sin(\omega_0 t)$ as the sum signal. However, this signal corresponds precisely to the real part of $(R+j\bullet I)\bullet e^{-j\cdot\omega_0 t}$. The real part of the complex multiplication of the control signal and mixing signal can thus be determined by ~~means of~~ the first multiplier, the second multiplier and the adder.

According to <u>an</u> ~~one~~ advantageous embodiment of the invention, the sum signal produced by the adder is then quantized by the quantization stage ~~in order in this way~~ to produce the real pulsed signal. In this case, it is advantageous for a noise level to be added to the input signal to the quantization stage. The pulse modulator is clocked at a sampling frequency ω_A <u>that</u> ~~which~~ must be considerably higher than the mixing frequency ω_0. Certain ratios of ω_0 to ω_A result in relaxation oscillations being formed in the pulse modulator. ~~and~~ These can be seen as additional peaks in the frequency spectrum of the pulsed signal. Since a noise signal is added to the input signal

to the quantizer, the result of the quantization process is statistically rounded. This trick makes it possible to prevent the formation of relaxation oscillations.

The quantization stage preferably carries out binary ~~quantization~~ or ternary quantization of its respective input signal. In the case of binary quantization, the pulsed signal may assume only the values 0 and 1. A pulsed signal is thus produced that ~~which~~ contains only positive voltage pulses. A ternary-quantized pulsed signal may assume the values -1, 0, 1. A pulsed signal such as this ~~thus~~ comprises both positive and negative voltage pulses. Ternary quantization is ~~thus~~ carried out whenever a pulsed signal is required with both positive and negative pulses.

The feedback unit preferably has a second multiplication stage that ~~which~~ multiplies the pulsed signal by a complex-conjugate mixing signal oscillating at the frequency ω_0. ~~and~~ It thus produces the feedback signal down-mixed by ω_0 for the subtractor. The pulsed signal is ~~was~~ produced by quantization of the real part of the up-mixed control signal, and thus has its dominant frequency component at the frequency ω_0. Before the pulsed signal can be used as a feedback signal, it must ~~therefore~~ be down-mixed again to baseband. For this purpose, the

pulsed signal is multiplied by a complex-conjugate mixing signal at the frequency ω_0 ~~in order in this way~~ to obtain a down-mixed complex feedback signal.

The second multiplication stage preferably has a third multiplier for production of the real part of the feedback signal and ~~has~~ a fourth multiplier for production of the imaginary part of the feedback signal. ~~with~~ The third multiplier multiplies ~~multiplying~~ the pulsed signal by the real part of the complex-conjugate mixing signal oscillating at the frequency ω_0. ~~and with~~ The fourth multiplier multiplies ~~multiplying~~ the pulsed signal by the imaginary part of the complex-conjugate mixing signal at the frequency ω_0. ~~In order~~ To shift that frequency component of the pulsed signal ~~which is~~ at the frequency ω_0 in the correct direction, the multiplication of the pulsed signal by the mixing signal must be carried out in complex form. The pulsed signal y(t) is a real signal, while the complex-conjugate mixing signal can be represented in the form [illegible]. The complex multiplication thus produces a complex feedback signal with the real part $y(t) \bullet \cos(\omega_0 t)$ and the imaginary part $y(t) \bullet \sin(\omega_0 t)$.

The pulse modulator is preferably operated at a sampling frequency ω_A which is 2 to 1000 times higher than

the mixing frequency ω_0. This is necessary ~~in order~~ to satisfy the Nyquist condition for the up-mixed signals.

According to a further advantageous embodiment, the pulse modulator is implemented with the aid of a digital signal processor (DSP). All of the operations which are required for operation of the pulse modulator can be programmed with the aid of signal processing routines.

The drive circuit according of ~~to~~ the invention for a micromechanical resonator has at least one pulse modulator of the type described above. The pulsed signal ~~which is~~ produced by the at least one pulse modulator is preferably used for electrostatic oscillation stimulation of the resonator. The pulsed signal ~~which is~~ produced can be directly connected to the stimulation electrodes of the resonator. In this case, it is advantageous for the mixing frequency ω_0 of the pulse modulator to correspond to one resonant frequency of the resonator, as ~~because~~ this then insures ~~ensures~~ effective stimulation of the oscillator.

A frequency generator in accordance with ~~according to~~ the invention for synthesis of a pulsed signal at a predetermined frequency ~~and~~ with a predetermined phase has at least one pulse modulator of

the type described above. The pulse modulator according to the invention can be used to produce a corresponding pulsed signal y(t) at a predetermined frequency ~~and~~ with a predetermined phase. In this case, the phase angle of the pulsed signal ~~that is~~ produced can be predetermined very precisely by ~~means of~~ the ratio of the real part to ~~and~~ the imaginary part of the input signal x(t). The pulsed signal ~~which is~~ produced has a low noise level in the vicinity of ω_0.

According to a further advantageous embodiment, the pulse modulator is followed by a bandpass filter, preferably a crystal or ceramic filter. This downstream bandpass filter allows those frequency components remote ~~which are further away~~ from ω_0 and in which the noise level is high to be filtered out.

While the invention has been described with reference to its presently-preferred embodiment, it is not limited thereto. Rather, the invention is limited only insofar as it is defined by the following set of patent claims and includes within its scope all equivalents thereof.

What is claimed is:

1. A pulse modulator for conversion of a complex input signal (x(t)) to a pulsed signal (y(t)), characterized by

- a subtraction stage (1) which produces a control error signal from the difference between the complex input signal (x(t)) and a feedback signal (2),
- a single conversion stage, which converts the control error signal to a control signal (7);
- a first multiplication stage (8), which multiplies the control signal (7) by a complex mixing signal oscillating at the frequency ω_0, and thus produces at least one of a real part (11) and an imaginary part of a control signal which has been up-mixed by ω_0;
- a quantization stage (12), which quantizes at least one of the real part and imaginary part of the control signal which has been up-mixed by ω_0 and thus produces the pulsed signal (y(t));
- a feedback unit, which uses the pulsed signal (y(t)) to produce the feedback signal (2) for the subtraction stage.

2. The pulse modulator as claimed in claim 1, characterized in that the pulse modulator has an in-phase signal path for processing of the real part of the input signal, as well as a quadrature signal path for processing of the imaginary part of the input signal.

3. The pulse modulator as claimed in claim 1 or 2, characterized in that the control error signal, the control signal and the feedback signal are each complex signals, which each have a real signal component as well as an imaginary signal component.

4. The pulse modulator as claimed in one of the preceding claims, characterized in that the signal conversion stage has an integrator stage which integrates the control error signal and produces an integrated signal as the control signal.

5. The pulse modulator as claimed in claim 4, characterized in that the integrator stage has a first integrator for the in-phase signal path (14) and a second integrator for the quadrature signal path (15), with the first integrator integrating the real part of the control error signal, and with the second integrator integrating the imaginary part of the control error signal.

6. The pulse modulator as claimed in one of the preceding claims, characterized in that the signal conversion stage has an amplifier stage (6).

7. The pulse modulator as claimed in one of the preceding claims, characterized in that the first multiplication stage has a first multiplier (23) for the in-phase signal path and a second multiplier (33) for the quadrature signal path, with the first multiplier multiplying the real part (22) of the control signal by the real part of the complex mixing signal oscillating at the frequency ω_0, and thus producing a first result signal (24), and with the second multiplier (33) multiplying the imaginary part (32) of the control signal by the imaginary part of the complex mixing signal oscillating at the frequency ω_0, and thus producing a second result signal (34).

8. The pulse modulator as claimed in claim 7, characterized by an adder (25) which adds the first result signal (24) from the first multiplier and the second result signal (34) from the second multiplier to form a sum signal (35) in order to determine the real part of the up-mixed control signal.

9. The pulse modulator as claimed in claim 8, characterized in that the quantization stage quantizes the sum signal produced by the adder.

10. The pulse modulator as claimed in one of the preceding claims, characterized in that a noise level is added to the input signal to the quantization stage.

11. The pulse modulator as claimed in one of the preceding claims, characterized in that the quantization stage carries out binary quantization or ternary quantization of its respective input signal.

12. The pulse modulator as claimed in one of the preceding claims, characterized in that the feedback unit has a second multiplication stage (13), which multiplies the pulsed signal by a complex-conjugate mixing signal oscillating at the frequency ω_0, and thus produces the feedback signal (2) down-mixed by ω_0, for the subtractor.

13. The pulse modulator as claimed in claim 12, characterized in that the second multiplication stage has a third multiplier (37) for production of the real part (17) of the feedback signal and has a fourth multiplier (38) for production of the imaginary part (27) of the feedback signal, with the third multiplier (37) multiplying the pulsed signal by the real part of the complex-conjugate mixing signal oscillating at the frequency ω_0, and with the fourth multiplier (38) multiplying the pulsed signal by the imaginary part of the complex-conjugate mixing signal at the frequency ω_0.

14. The pulse modulator as claimed in one of the preceding claims, characterized in that the pulse modulator is operated at a sampling frequency ω_A which is 2 to 1000 times higher than the mixing frequency ω_0.

15. The pulse modulator as claimed in one of the preceding claims, characterized in that the pulse modulator is implemented with the aid of a digital signal processor.

16. A drive circuit for a micromechanical resonator which has at least one pulse modulator as claimed in one of claims 1 to 15.

17. The drive circuit as claimed in claim 16, characterized in that the pulsed signal which is produced by the at least one pulse modulator is used for electrostatic oscillation stimulation of the resonator.

18. The drive circuit as claimed in claim 16 or 17, characterized in that the mixing frequency ω_0 of the pulsed modulator corresponds to one resonant frequency of the resonator.

19. A frequency generator for synthesis of a pulsed signal at a predetermined frequency and with a predetermined phase, which has at least one pulse modulator as claimed in one of claims 1 to 15.

20. The frequency generator as claimed in claim 19 or 20, characterized in that the pulse modulator is followed by a bandpass filter, preferably a crystal or ceramic filter.

21. A method for pulse modulation of a complex input signal, characterized by the following steps:

- production of a control error signal from the difference between the complex input signal (x(t)) and a feedback signal (2);
- conversion of the control error signal to a control signal (7);
- multiplication of the control signal (7) by a complex mixing signal oscillating at the frequency ω_0, with at least one of the real part (11) and imaginary part of a control signal, up-mixed by ω_0, being produced;
- quantization of at least one of the real part (11) and imaginary part of the control signal, up-mixed by ω_0, in order to produce a pulsed signal (y(t));
- production of the feedback signal (2) from the pulsed signal (y(t)).

22. The method as claimed in claim 21, characterized in that the control error signal, the control signal and the feedback signal are each complex signals, which each have a real signal component as well as an imaginary signal component.

23. The method as claimed in claim 21 or claim 22, characterized in that the control error signal is converted to the control signal by integrating the control error signal.

24. The method as claimed in one of claims 21 to 23, characterized in that the real part of the control signal is multiplied by the real part of the complex mixing signal oscillating at the frequency ω_0, and a first result signal is thus produced, and in that the imaginary part of the control signal is multiplied by the imaginary part of the complex mixing signal oscillating at the frequency ω_0, and a second result signal is thus produced.

25. The method as claimed in claim 24, characterized in that the first result signal and the second result signal are added to form a sum signal in order to determine the real part of the up-mixed control signal.

26. The method as claimed in claim 25, characterized in that the sum signal is quantized in order to produce the pulsed signal.

27. The method as claimed in one of claims 21 to 26, characterized in that a noise level is added before the quantization of at least one of the real part and imaginary part of the control signal up-mixed by ω_0.

28. The method as claimed in one of claims 21 to 27, characterized in that the feedback signal is produced by multiplying the pulsed signal by a complex-conjugate mixing signal oscillating at the frequency ω_0.

29. The method as claimed in one of claims 21 to 28, characterized in that the pulsed signal is used for electrostatic oscillation stimulation of a micromechanical resonator.

30. The method as claimed in claim 29, characterized in that the mixing frequency ω_0 corresponds to one resonant frequency of the micromechanical resonator.

31. A computer program product, which has means for carrying out the method steps as claimed in one of claims 21 to 30 on a computer, a digital signal processor or the like.

ABSTRACT

~~Pulse modulator and method for pulse modulation~~

A ~~The proposed~~ pulse modulator has a subtraction stage that ~~which~~ produces a control error signal from the difference between a ~~the~~ complex input signal and a feedback signal. ~~as well as~~ A signal conversion stage ~~which~~ converts the control error signal to a control signal. The control signal is multiplied by a complex mixing signal at the frequency ω_0 in a first multiplication stage. At least one of the real ~~part~~ and imaginary parts ~~part~~ of the up-mixed control signal is ~~or are~~ then quantized by a quantization stage ~~in order~~ to produce a real pulsed signal. ~~in this way~~ The pulsed signal is then employed ~~used~~ to produce the feedback signal for the subtraction stage in a feedback unit. The pulse modulator according to the invention allows the range of reduced quantization noise to be shifted toward a desired operating frequency ω_0.

~~(Figure 2)~~